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The temperature and concentration of charged particles in the plasma of a DC arc burning under water are measured from the emission spectrum of copper. The possible errors of measurement are estimated. A method of allowing for the self-absorption of the lines in the temperature determination is given. The Stark constants are calculated for a number of lines, and it is shown that the theoretical values should be used in measuring the concentration of charged particles. author

It appears expedient to develop methods of plasma diagnostics under arc discharge conditions from the emission spectrum of copper, since copper vapor formed by erosion of the electrodes is present in plasma devices of all kinds (plasmatrons, magnetohydrodynamic generators, arcs, etc.). In this connection it becomes necessary to select the appropriate spectral lines, refine their principal constants (transition probabilities, Stark constants, van der Waals constants), estimate the effect of various factors on the broadening of the selected lines, and find the errors of measurement of the temperature and concentration of charged particles.

For the experimental solution of the problems posed, we selected a DC arc (i = 8 amp) between copper or brass electrodes under water. Under these condi-

* Numbers in the margin indicate pagination in the original foreign text.

tions, we observed a rather intense emission spectrum of copper with appreciably broadened lines, which – the most important consideration – permitted rather reliable measurement of the concentration of charged particles from the broadening of the H_β hydrogen line. The emission spectra were registered by a DFS-13 spectrograph with a 600 line/mm diffraction grating (linear dispersion 4 Å/mm and instrument broadening somewhat less than 0.1 Å); the spectrograph slit was set at 0.02 mm. A single-lens slit illuminator was used, which averaged the radiation over the line of sight but not over the entire discharge cloud. The spectra were photographed on Iso-ortho plates of 65 State Standard (GOST) units. The exposures ranged from 20 sec to 5 min. The region of the spectrum registered was from 4280 to 5150 Å. Heterochromatic photometry was not performed, since the sensitivity variation of the plates used was small in the investigated spectral interval. The constant length of the discharge gap was adjusted by means of a specially designed electrode holder, permitting its variation without shifting the center of the arc away from the optical axis. The electrode holder was placed in a glass tank containing ordinary tap water, in such a way that the discharge gap was at a depth of 8 – 10 cm and right up against the tank wall.

The source selected was not without shortcomings. The arc channel continuously changed its position in space, making it impossible to estimate the intensity along the arc radius; thus, the intensities obtained were the result of averaging not only over the line of sight but also over time. This necessarily showed in our results. Nevertheless, the above problems could be solved, in /521 first approximation, even with such a source.

The emission spectrum of the copper arc under water contains the lines 5163.2, 5105.5, 4704.6, 4530.8, 4480.4, 4275.1 Å, etc. of the neutral copper atom. A rather intense hydrogen line H_β is also present. This hydrogen line is very faint in the emission spectrum of an arc between brass electrodes.

Out of all the lines we selected those lines of the neutral copper atom that were located relatively close together, covered a large interval of excitation energies of the upper levels, and had known experimental or theoretical

TABLE 1

λ, Å	Serial Transition	E_i, cm^{-1}	gA, 10^8 sec^{-1}	gf	C_4, cm^4 sec^{-1}: Accd. to Holtsmark and Trumpy	C_4, cm^4 sec^{-1}: Theoretical	C_4, cm^4 sec^{-1}: Experimental, from H_β	C_6, cm^6 sec^{-1}: Interaction with H atoms	C_6, cm^6 sec^{-1}: Interaction with O atoms
4022.7	$4^2P_{1/2} - 5^2D_{3/2}$	30535—55388	0.77	0.19	$1.55\cdot10^{-}$[illegible]	$1.64\cdot10^{-}$[illegible]	$1.1\cdot10^{-}$[illegible]	$1.5\cdot10^{-}$[illegible]	$2.2\cdot10^{-}$[illegible]
4275.1	$z^4P_{5/2} - {}^4D_{5/2}$	30319—62403	2.6	0.72	$1.83\cdot10^{-}$[illegible]	[illegible]	[illegible]	$1.6\cdot10^{-}$[illegible]	$2.4\cdot10^{-}$[illegible]
4480.4	$4^2P_{1/2} - 6^2S_{1/2}$	30535—52849			$7.95\cdot10^{-}$[illegible]	$1.08\cdot10^{-}$[illegible]	$2.68\cdot10^{-}$[illegible]		
4530.8	$4^2P_{3/2} - 6^2S_{1/2}$	30784—52849	0.65	0.20					
5105.4	$m^2D_{5/2} - 4^2P_{3/2}$	11203—30784	0.051	0.020					
5153.2	$4^2P_{1/2} - 4^2D_{3/2}$	30535—49935	4.7	1.9					

values for the principal constants, namely, the transition probabilities and the constants of the various types of interaction. Table 1 gives the data for the lines that more or less satisfy these requirements. The transition probabilities are taken from Corliss (Bibl.1) and the experimental values of the Stark constants from two other papers (Bibl.2, 3). The theoretical values of the Stark constant were calculated on the basis of the theory of perturbation in second approximation, under the assumption that the field is weak for the S, P and D levels and strong for the F levels. The matrix elements were determined according to Bates and Damgaard (Bibl.4). Table 1 gives the resulting constants for the lines as a whole, found after allowing for the relative intensities of the components due to Stark splitting. The theoretical values of the Stark constants are more than one order smaller than the values given by Holtsmark and Trumpy (Bibl.2). The same great discrepancy between the theoretical and experimental values for the Stark constants was also noted earlier for oxygen and nitrogen (Bibl.5). In the case of the copper atom, good agreement is observed for the line 4022.7 Å between the theoretical values of the constants and the experimental values calculated from the shift of the maxima of the lines in another paper (Bibl.3).

The van der Waals constants were calculated using the effective principal quantum numbers according to Bates and Damgaard (Bibl.4). The values of the polarizability for oxygen are taken from Alpher (Bibl.6) and for hydrogen from Landau (Bibl.7).

The temperature of the arc was determined from two pairs of copper lines, 5105.5, 5153.2 Å and 5105.5, 4530.8 Å. This permitted us to define the extent of self-absorption in the lines, since if there were self-absorption we would get lower values from the first pair of lines and exaggerated values from the second. However, the temperatures found from the first and second pairs of lines were in fact the same: $T = 6600 \pm 500°K$. This means that self-absorption exerts no substantial influence on the temperature measurements. We verified in advance that the Boltzmann distribution of atoms by excitation energies was valid here, using the method proposed elsewhere (Bibl.8).

A marked broadening of the copper lines at 4530.8 and 4480.4 Å was observed. Table 1 gives the corresponding transitions for these lines. Table 2 /522 shows the manner in which the various types of interaction affect the broadening of these lines. The influence of the Stark quadratic effect under the action of ions and electrons was estimated from the concentration of charged particles in the plasma, measured from the width of the H_β line, while the Stark constant used was the theoretical value. The effect of the van der Waals forces was estimated under the assumption that the pressure in the plasma of the arc discharge was equal to the pressure in the surrounding medium, i.e., 1 atm. The resonance interaction was estimated under the assumption that the vapor of the electrode material was about 10% of the plasma*. The Doppler broadening was determined for a plasma temperature of 7000° K.

TABLE 2

No.	Type of Interaction	Theory of Broadening Applied	Half-Width, Å 4530	Half-Width, Å 4480	Form of Contour
1	Quadratic Stark effect: a) under the influence of ions	Statistical	0.05	0.05	Asymmetry in the red spectrum region
	b) under the influence of electrons	Collision	0.9	0.9	Symmetry relative to line maximum
2	Resonance interaction	Collision	0.016	0.005	Symmetry relative to line center
3	van der Waals interaction with atoms of hydrogen and oxygen	Collision	0.04	0.04	Symmetry relative to line maximum
4	Doppler broadening		0.04	0.04	Symmetry relative to line center

TABLE 3

Cu I λ 4530.8 Å			Cu I λ 4480.4 Å			H_β
Half-Width of Line, Å	Concentration of Charged Particles (cm^{-3}) at Values of the Stark Constant: Theoretical	Concentration of Charged Particles (cm^{-3}) at Values of the Stark Constant: According to Holtsman and Trumpy	Half-Width of Line, Å	Concentration of Charged Particles (cm^{-3}) at Values of the Stark Constant: Theoretical	Concentration of Charged Particles (cm^{-3}) at Values of the Stark Constant: According to Holtsman and Trumpy	Concentration of Charged Particles, cm^{-3}
0.40	$1.07 \cdot 10^{16}$	$3 \cdot 10^{15}$	0.51	$1.6 \cdot 10^{16}$	$8 \cdot 10^{14}$	$2.8 \cdot 10^{16}$
0.44	$1.15 \cdot 10^{16}$	$3.5 \cdot 10^{15}$	0.64	$1.7 \cdot 10^{16}$	$9 \cdot 10^{14}$	$2.5 \cdot 10^{16}$
0.64	$1.7 \cdot 10^{16}$	$4\ 5 \cdot 10^{15}$	1.36	$3.8 \cdot 10^{16}$	$2 \cdot 10^{15}$	$6.2 \cdot 10^{16}$

* Customarily considered 1 - 2% in an arc under atmospheric pressure.

An analysis of Table 2 shows that the line broadening is due primarily to the quadratic Stark effect. This is indicated by the fact that the line is appreciably asymmetric in the red spectrum region. The effect of other types of interaction, like the effect of instrumental broadening, may be assigned to the error of measurement of the line width.

Since the line broadening is due to the influence of the quadratic Stark effect (mainly to collision interaction of the electrons), the Stark constant for these lines can be found from the concentration of charged particles determined from the H_β lines. Table 1 gives the values of this constant. It differs by a factor of 4 from the theoretical values, and by a factor of 68 from the values given by Holtsmark and Trumpy. Before selecting the particular value of the Stark constant to be taken for the measurement of the concentration of charged particles in the plasma, we will determine the concentration of charged particles using various values of the constant. Table 3 gives the results of these calculations. The calculations were performed under the assumption that the total width of a line is made up almost additively of the broadening under the influence of the electrons and ions, with the ions forming quasi-static /523 fields by means of which they act on the radiating atom and with the electrons causing collision broadening of the spectral lines (Bibl.9). The non-adiabaticity, as shown by an estimate (Bibl.10), can be neglected considering that the Lindholm-Weiskopf theory of collision broadening is valid for these lines.

It must be borne in mind that the excitation potential of the hydrogen line H_β is 12.7 ev, while it is 6.55 ev for the copper lines. Effective excitation of these lines therefore takes place in various domains of the arc discharge. Hydrogen will be excited mainly in the discharge tunnel, where the highest temperatures and charged-particle concentrations occur, while the copper lines will be excited throughout the discharge cloud. It follows that the charged-particle concentrations determined from the time-average values of the spectral line widths must differ from those concentrations determined from the widths averaged along the line of sight. The charged-particle concentration found from the copper lines should be somewhat smaller than the value calculated from the broadening of the H_β line. This is in fact the case if we use the theoretical value of the Stark constant. Theoretical calculations, even though not exact, should still give the correct order of magnitude. Their error will probably not exceed several tens of percent.

The Stark constants given by Holtsmark and Trumpy are very rough. Their values for the lines 4530.8 and 4480.4 Å differ by a factor of two, which should not be so since the upper level whose shift primarily determines the line broadening is the same in both cases. It was found that other lines are superposed on the red end of the line 4480.4 Å, and have only a small effect on the broadening in the case of small fields but a substantial influence in the case of large fields, making the line 4480.4 Å more than twice as wide as the line 4530.8 Å (see Table 3). This is probably why Holtsmark (Bibl.2) gives different values for the Stark constants. This makes it impossible to use the line 4480.4 Å in determining the charged-particle concentration in a plasma containing copper vapor if the electric intermolecular fields are large. The determination of the Stark constants from the line broadening under arc-discharge conditions, if the charged-particle concentration is found from the current, evidently gives exaggerated values, thus explaining the discrepancy between the Stark constants observed by Stampa (Bibl.5) and in the present work.

Using the theoretical values of the Stark constants and averaging the data of Table 3, we find the values $(1.3 \pm 0.3)\ 10^{16}\ cm^{-3}$ for the charged-particle concentration in the plasma of a DC arc burning between copper electrodes under water. Here the indicated error of measurement is due primarily to the inaccuracy of the line-width determination. The charged-particle concentration is higher than in the same arc burning in the atmosphere, for which a value of 10^{15} cm^{-3} is generally taken (Bibl.11). Their temperature here is about 1500°K higher.

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